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Direct measurement of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ cross section into the s -process Gamow peak

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One of the main neutron sources for the astrophysical s -process is the reaction $^{13}\text{C}(\alpha, n)^{16}\text{O}$, taking place in thermally pulsing Asymptotic Giant Branch stars at temperatures around 90 MK. To model the nucleosynthesis during this process the reaction cross section needs to be known in the 150-230 keV energy window (Gamow peak). At these sub-Coulomb energies cross section direct measurements are severely affected by the low event rate, making us rely on input from indirect methods and extrapolations from higher-energy direct data. This leads to an uncertainty in the cross section at the relevant energies too high to reliably constrain the nuclear physics input to s -process calculations. We present the results from a new deep-underground measurement of $^{13}\text{C}(\alpha, n)^{16}\text{O}$, covering the energy range 230-300 keV, with drastically reduced uncertainties over previous measurements and for the first time providing data directly inside the s -process Gamow peak. Selected stellar models have been computed to estimate the impact of our revised reaction rate. For stars of nearly solar composition, we find sizeable variations of some isotopes, whose production is influenced by the activation of close-by branching points that are sensitive to the neutron density, in particular the two radioactive nuclei ^{60}Fe and ^{205}Pb , as well as ^{152}Gd .

Low-mass Asymptotic Giant Branch (AGB) stars are thermal pulses (TPs). Each He-flash generates a large major production sites of heavy elements in the Universe convective zone that mixes the C produced by the triple- α (for a recent review see [1]). Their interior contains a reaction up to the top of the He mantel. Later on, the carbon-oxygen core surrounded by a thin He-rich mantel shell-H burning, always active at the base of the envelope, and a H-rich envelope. Periodically, these stars undergo dies down and, in turn, the external convection penetrates thermonuclear instabilities, He-burning flashes, called the He-rich mantel. This phenomenon, which moves the

nucleosynthesis yields up to the stellar surface, is called the *third dredge up*. As early recognized, the creation of a ^{13}C -pocket within the He-rich mantel, through the reaction $^{12}\text{C}(\text{p},\gamma)^{13}\text{N}(\beta^+)^{13}\text{C}$, is a byproduct of these recursive mixing episodes [2, 3]. Such a thin pocket (a few $10^{-5}M_{\odot}$ of ^{13}C) harbors one of the most important nucleosynthesis sites in the Universe. During the period between two TPs, the temperature attains about 90 MK and ^{13}C is activated as a neutron source through the reaction $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$. This process provides a relatively slow neutron flux ($\approx 10^7$ neutrons/s/cm 2) for about 10^4 years each time. Starting from seed nuclei in the iron region, this neutron flux slowly builds up heavy elements along the line of stability [4]. This *s*-process (*slow-neutron-capture*) is responsible for the production of about half of all the heavy elements ($A \geq 90$) in the Universe.

In order to constrain this important nucleosynthesis process, the cross section of the $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$ neutron source needs to be known in the astrophysical energy window (the Gamow peak) around $E_0 = 150\text{--}230$ keV 1 . The available direct cross section data in the lower energy interval $280 < E < 350$ keV [5, 6] are affected by uncertainties $\geq 40\%$. Any effort of pushing direct reaction measurements to lower energies is basically rendered futile by the steep drop of the cross section and the presence of natural and instrumental backgrounds. Extrapolation of the cross section into the Gamow peak is further complicated by a broad state at $E_x = 6356(8)$ keV ($J^\pi = \frac{1}{2}^+$) just near the α -threshold in ^{17}O ($S_\alpha = 6359$ keV [7]). The cross section evaluation in the Gamow peak requires a careful matching between the tail of this near-threshold state and the higher-energy experimental data. While this state has been the focus of great experimental attention over the past years [8–12] its influence remains a major source of uncertainty for the *s*-process [13] and the need for more cross section data to fill the gap has been frequently expressed [13, 14].

In order to provide direct data at low energies to better constrain the cross section inside the Gamow peak the LUNA collaboration has performed an intensive experimental campaign at the deep-underground accelerator LUNA400 [15] inside the Gran Sasso National Laboratory (LNGS). The LNGS neutron background flux ($\approx 10^{-7}$ n/cm 2 /s) [16] is dominated by the natural radioactivity of the surrounding rock and it is up to four orders of magnitude lower than on the surface of the Earth, improving the sensitivity over previous studies.

The experimental setup and the target analysis are described in detail in refs. [17–19], following is a brief summary. The accelerator provided a He^+ beam on target up to 150 μA with α energies of 305–400 keV, corresponding to c.m. energies in the range 233–306 keV. Deposited

charges vary from 15 C at the highest to 90 C at the lowest energy. The beam impinged upon water-cooled targets made of an 99% enriched ^{13}C evaporated on a 0.2 mm thick Ta backing [17].

Near the target, the beam passed a liquid nitrogen cooled shroud and an electrically insulated collimator at a negative voltage of 300 V (to suppress the effects of secondary electrons). The neutrons produced by the $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$ reaction, with energies around 2.4 MeV, were thermalized in a polyethylene moderator and detected by 18 ^3He -filled proportional counters with stainless steel housing. Two geometrical detector configurations (a vertical and a horizontal orientation) were used to optimize the absolute neutron detection efficiency, $34 \pm 3\%$ and $38 \pm 3\%$, respectively [18]. Moreover, the measurement reproducibility was checked by separately analysing datasets acquired with the two detector configurations at the same energy, finding agreement in the final results. The detector signals were digitized with a 100 MHz sampling rate and analyzed offline to suppress the internal background from α -decays in the steel housing of the counters using a custom pulse-shape discrimination (PSD) technique [20]. The PSD in combination with the borated polyethylene shielding (5 and 10 inches, depending on the setup) around the detector as well as the underground location results in a total background rate inside the neutron signal region of 1.2 ± 0.1 counts/hour for both configurations, leading to an improvement by more than two orders of magnitude compared with previous experiments.

Blank backings were irradiated obtaining a background level of 1.3 ± 0.2 counts/hour, in agreement with the environmental one. The conclusion was that beam induced background was negligible. The evaporated ^{13}C targets were characterized in term of homogeneity and thickness immediately after the evaporation at ATOMKI by means of the $^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$ resonance at $E_{\text{r,lab}} = 1748$ keV. The average target thickness at resonance energy was 5 keV, corresponding to 170 nm. Because of the cross section reduction of one order of magnitude, the differential neutron yield becomes negligible from reactions occurring beyond 150 nm inside the target, so all the targets can be considered to be of the same effective thickness. At LUNA, target quality was frequently checked (every 1.5 C accumulated charge) using direct γ -ray measurements of the $^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$ reaction [17].

The cross section was calculated as follows:

$$Y = \frac{\eta(E_\alpha)}{Qe} \int_{E_\alpha - \Delta E}^{E_\alpha} \frac{\sigma(E)}{\epsilon_{\text{eff}}(E)} dE, \quad (1)$$

where Y is the number of detected neutrons per projectile (PSD corrected), η the neutron detection efficiency, Qe is the incident number of particles on the target, E_α the beam energy, $\epsilon_{\text{eff}}(E)$ the effective stopping power and ΔE the projectile energy loss in the target.

The maximum accumulated α -charge on each target was limited to 3 C, corresponding to at most a 30% degrada-

¹ All energies in this manuscript are center-of-mass energies, unless explicitly stated otherwise.

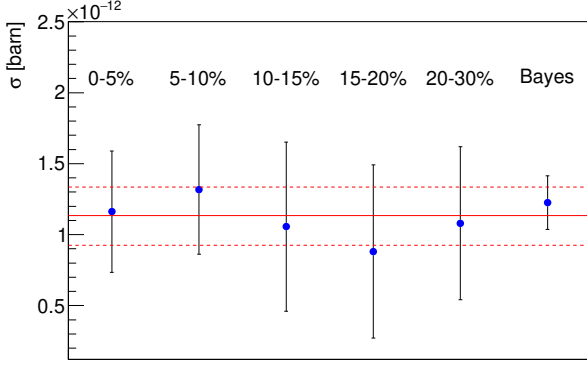


FIG. 1. Comparison of the cross section at 233 keV for different target degradation and the Bayesian results. The solid and dashed lines represent the weighted average of the groups and the corresponding uncertainty, respectively.

dation. The lowest energies $E = 245$ and $E = 233$ keV required special attention, as the statistics collected during a single run was insufficient to obtain a reliable estimate of the cross section. Two independent approaches were used in the analysis. In the first one, all runs at the same energy with similar target degradation levels were summed together and the cross sections for each “subset” were calculated and combined to the cross section for this energy. In the second one, the two lowest energies were also analyzed using a Bayesian approach [21], see the corresponding section in the supplemental material for details.

In Figure 1, the 233 keV cross section results as a function of the target degradation are compared with the Bayesian analysis’ result. The mean values of the cross section are in agreement; the “grouping” method was used for the extraction of the cross sections presented later in this work.

The experimental results are summarized in Table I, where we also show the S -factor² after correcting for the electron screening effect³ (bare in Table I), following refs. [22–24]. The Table includes statistical and systematic uncertainties. The latter are: 3% for the charge integration, 5% for stopping power calculated with SRIM-2010 [25] and about 8% for the detection efficiency. The uncertainty of the beam energy is around 300 eV, and the beam energy spread is less than 100 eV [15].

The new data extend the energy range covered by direct cross-section measurements into the s -process Gamow

TABLE I. Experimental and electron screening-corrected S -factors measured in this work. In the Table the data format is $\text{data} \pm \text{stat} \pm \text{syst}$, where syst is a common systematic uncertainty of 10 % (further details in the text).

| Energy [keV] | S -factor [10^5 MeV b] | S -factor [10^5 MeV b] (bare) |
|-----------------|---|---|
| 306 | $8.06 \pm 0.18 \pm 0.8$ | $7.61 \pm 0.17 \pm 0.8$ |
| 298 | $8.1 \pm 0.3 \pm 0.8$ | $7.6 \pm 0.3 \pm 0.8$ |
| 291 | $7.3 \pm 0.3 \pm 0.7$ | $6.8 \pm 0.3 \pm 0.7$ |
| 283 | $8.6 \pm 0.3 \pm 0.9$ | $8.0 \pm 0.3 \pm 0.8$ |
| 275 | $9.2 \pm 0.6 \pm 0.9$ | $8.6 \pm 0.5 \pm 0.9$ |
| 260 | $8.7 \pm 0.8 \pm 0.9$ | $8.1 \pm 0.7 \pm 0.8$ |
| 245 | $11.7 \pm 1.7 \pm 1.2$ | $10.8 \pm 1.5 \pm 1.1$ |
| 233 | $12.7 \pm 2.3 \pm 1.3$ | $11.6 \pm 2.1 \pm 1.2$ |

TABLE II. R-matrix parameters and data sets.

| E_x [keV] | Γ_n [keV] | Γ_α [ANC [keV]][fm $^{-1/2}$] | Dataset | Norm. |
|----------------|---------------------|---|-------------------|-------|
| 6356 | 124 | 5.44×10^{90} | Drotleff [5] | 1 |
| 7215 | 305.3 | 9.75×10^{-2} | Heil [6] | 1 |
| 15000 | 2.42×10^4 | 6.04×10^5 | Harissopulos [27] | 1.37 |
| 15000 | 4.33×10^2 | 6.02×10^5 | This work | 1 |

peak, but an extrapolation towards zero energy, also taking into account the near-threshold state ($E_x = 6356$ keV, $J^\pi = \frac{1}{2}^+$), is still required. This was done with an R-matrix analysis using the code Azure2 [26]. The low-energy cross section is dominated by two broad states, the already mentioned near-threshold state and a $\frac{3}{2}^+$, $E_x = 7215$ keV one. Narrow resonances in the energy range covered by the analysis ($E < 1.2$ MeV) do only have very localized effects on the cross sections and were omitted. As the threshold state was assumed to be α -bound, an asymptotic normalization coefficient instead of an α partial width was used [10]. Energy and width or asymptotic normalization constant (ANC) of the threshold state were kept fixed (note that they were varied in the Monte Carlo analysis, see below). Channel radii of 4.15 fm and 6.684 fm were used for the neutron and α channels, respectively. In addition to the cross sections from Heil and Drotleff, the data by Harissopulos [27] were included in the analysis, as they cover a wider energy range and help better constrain the ≈ 800 keV resonance. A normalization factor of 1.37 was applied to the latter to match the absolute scales of the different data sets. Two high-energy poles were included to take into account the influence of higher-lying resonances on the cross section. Their widths and that of the $E_x = 7215$ keV state were kept free. The parameters resulting from the R-matrix fit are given in Table II. The top panel of Figure 2 shows the experimental S factors and the R-matrix fits with (solid line) and without (dashed line) our new LUNA data.

The uncertainties in the final cross section were inves-

² The astrophysical S -factor is defined as $\sigma(E) = S(E) \frac{1}{E} e^{-2\pi\eta}$ and is commonly used to remove the strong energy dependence in the cross section due to the Coulomb repulsion. $\eta = 0.1575 Z_a Z_b \sqrt{\frac{1}{E} \frac{M_a M_b}{M_a + M_b}}$ is the Sommerfeld parameter.

³ A screening potential of 937 V was used for the calculations: the corresponding correction is less than 10% for all the energies.

178 tigated using a Monte Carlo (MC) approach. The ANC
 179 and the neutron partial width of the threshold state, as
 180 well as the absolute scales of the four experimental data
 181 sets, were randomly sampled from a Gaussian distribution
 182 according to their respective uncertainties. To be conser-
 183 vative, a 12% uncertainty was assumed for the absolute
 184 scale of each data set. 30000 MC variations were eval-
 185 uated and the R-matrix cross sections of each run were
 186 saved for later processing. The density map of the results
 187 and traditional 1σ contours are displayed in Figure 2. As
 188 mentioned above, the cross sections from [27] are rescaled
 189 to match the [5] and [6] data, as in other recent papers.
 190 However, there are no strong motivations for doing so,
 191 and one could choose to instead base the normalization
 192 on the Harissopulos et al. data (as suggested by a recent
 193 measurement [28]). To investigate the effect of the two dif-
 194 ferent normalizations we performed R-matrix calculation
 195 using data by Harissopulos et al. as a reference for the
 196 normalization of [5] and [6]. Inside the Gamow peak, the
 197 effect is only of the order of 5%, increasing towards higher
 198 energies. The absolute scale of the normalization of the
 199 historical data is still a matter of debate. Therefore in
 200 the MC procedure, only for the sake of the determination
 201 of a lower limit, we also considered the case (for half of
 202 the total trials) of using unscaled Harissopulos *et al.* [27]
 203 data, while the [5] and [6] normalizations were changed
 204 accordingly. It is worth noting that this additional source
 205 of uncertainty contributes only marginally, about 5%, at
 206 the s -process energies, where the cross section is well
 207 constrained by the present data, while it has a larger
 208 impact at higher energies⁴. As will be discussed below,
 209 the establishment of a reliable lower limit is crucial for
 210 the determination of possible nucleosynthesis variations.
 211 In total, three different rates were calculated: “LUNA”
 212 using the R-matrix best fit including the new cross sec-
 213 tions, “no-LUNA”, the best fit without the new data, and
 214 “low-LUNA” using the 5th percentile of the fit adopting
 215 the Harissopulos normalization. The “no-LUNA”, and
 216 “low-LUNA” cover approximately the $\pm 95\%$ percentiles
 217 around the best fit.

218 Finally, the astrophysical reaction rate $R = N_A \langle \sigma v \rangle$ as
 219 a function of stellar temperature was calculated (in units
 220 of $\text{cm}^3 \text{mol}^{-1} \text{s}^{-1}$) by integration of the R-matrix cross-
 221 section:

$$R = \frac{3.7318}{T_9^{3/2}} \sqrt{\frac{M_0 + M_1}{M_0 M_1}} \times \int_0^\infty E \sigma(E) e^{-11.605 E / T_9} dE, \quad (2)$$

222 where T_9 is the temperature in GK, the energy is given in
 223 MeV, the cross section σ in b and the M_i are the atomic

⁴ New measurements of the higher-energy cross section are planned
 at various facilities worldwide, including with the upcoming
 LUNA MV accelerator at the LNGS[29], addressing this un-
 certainty.

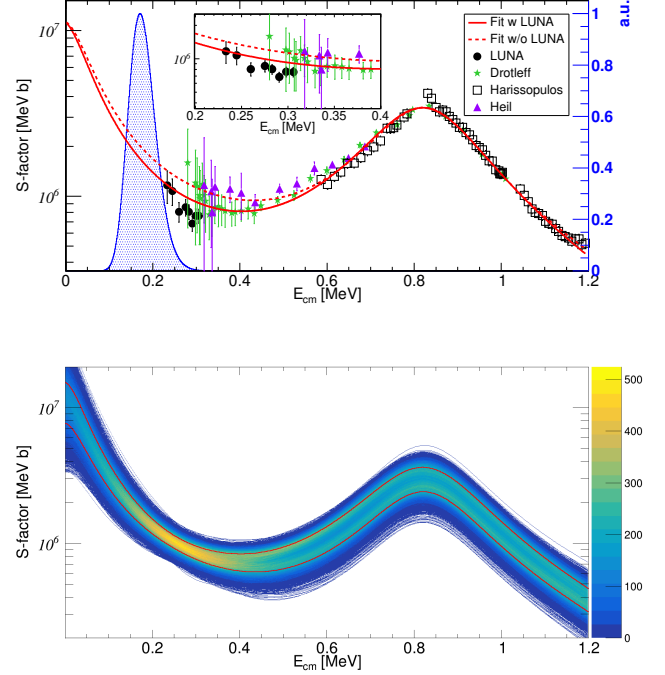


FIG. 2. Top: Astrophysical S -factor of $^{13}\text{C}(\alpha, n)^{16}\text{O}$. The lines show the results of two R-matrix analyses, with and without the new data. The Harissopulos dataset was normalized according to value in Table II. The blue curve is the “Gamow peak” at 90 MK and the right y axis refers to its relative scale. Bottom: Monte Carlo probability density for the S -factor.

masses of the reaction partners. Probability density functions for the rate were generated based on the results of the various MC cross sections. The contributions from the narrow resonances were as usual summed to the final rate. Tabulated results are shown in the supplemental material accompanying this Letter.

In the s -process in AGB stars [3, 30], shortly after a third-dredge-up episode, a ^{13}C -pocket forms within the He-rich mantel. During the following interpulse period, this region heats up and, around ~ 80 -100 MK, the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction starts to release neutrons. The high neutron exposure ($\sim 0.4 \text{ mb}^{-1}$ in solar metallicity stars) coupled to a low neutron density (a few 10^6 n/cm^3) are the two major features of the resulting s -process nucleosynthesis. The first ensures a neutron flux over a time long enough to produce a large overabundance of all the elements belonging to the main component of the s -process ($A > 90$), while the second favors β^- decays over neutron captures at the various branching points of the s -process path. In most cases, the ^{13}C -pocket is fully consumed during the interpulse period. However, if a small amount of ^{13}C survives (i.e., if the reaction rate is low enough), it will be engulfed into the convective shell powered by the subsequent thermal pulse and burned at a higher temperature (~ 200 MK) [31]. This second (convective) neutron burst is characterized by a higher neutron density ($> 10^9$

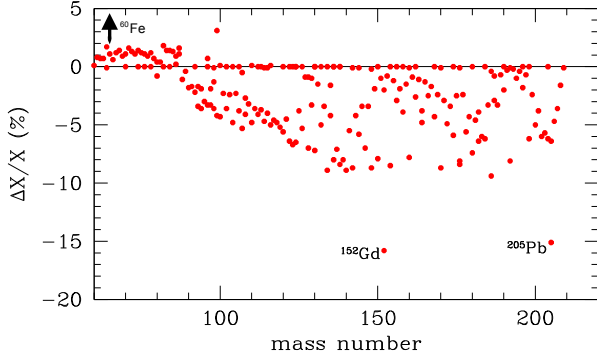


FIG. 3. Percentage variations of the mass fractions of heavy isotopes in the low-LUNA model with respect to the NO-LUNA model. In both models, the final surface composition is the cumulative result of 11 third dredge up episodes. The ^{60}Fe variation (+102%) is out of the scale and marked by an arrow.

n/cm^3) but much lower neutron exposure, than the main (radiative) event. As a consequence, it does not modify the bulk of stellar yields, but may affect some key isotopes at the s -process branching points [32]. Extant models of low-mass AGB stars have shown that this second neutron burst may occur during the first few thermal pulses, in stars with metallicity $Z \geq 0.01$ and that its efficiency is sensitive to the adopted $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction rate [14].

In order to evaluate the impact of the new reaction rate on the s -process, we have calculated three models of an AGB star with mass $M=2 M_{\odot}$, metallicity $Z=0.02$ and $Y=0.27$, under the three different assumptions (“LUNA” and the $\sim \pm 95\%$ values corresponding to “no-LUNA” and “low-LUNA”) for the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ rate mentioned above. In all the three models, some ^{13}C survives at the end of the first two interpulse periods and is burned at high temperature in the convective thermal pulse. Stronger effects of this second neutron burst are expected for the low-LUNA case. The results are compared in Figure 3.

Most of the nuclei belonging to the main component are depressed when the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ rate is lowered. This is the natural consequence of the suppression of the radiative s -process. The reduction of the surface abundances is stronger for the heavier isotopes ($A > 130$). The heavy- s (Ba, La, Ce, Nd, Sm) to light- s (Sr, Y, Zr) abundance ratio is an important spectroscopic index, often used to probe the mean neutrons to seeds ratio of an s -process site [33]. At the end of the AGB phase, the [heavy- s /light- s] ratio of the low-LUNA model is $\sim 6\%$ smaller than in the no-LUNA model. The abundance variations are generally small ($\leq 10\%$), with interesting exceptions, i.e., ^{60}Fe , ^{152}Gd and ^{205}Pb . All these isotopes are sensitive to the neutron density because of the existence of close-

by branching points. ^{152}Gd cannot be produced by the r -process and, except for a small p -process contribution, is mainly synthesized by the s -process. On the other hand, ^{60}Fe and ^{205}Pb are short-lived radioactive isotopes that were found to be alive in the early solar system [34]. The ^{60}Fe is produced when the neutron density is high enough to allow neutron captures at the ^{59}Fe branching point (half-life 44.5 d). Therefore, its final abundance is enhanced in case of the activation of the second (convective) neutron burst. With respect to the no-LUNA model, we find that the ^{60}Fe final mass fraction is a 30% higher, in the LUNA model, and a factor of 2 higher, in the low-LUNA model. On the contrary, the production of both ^{152}Gd , and ^{205}Pb requires low neutron density, while they are mainly destroyed in case of high neutron density. Indeed, the first isotope is bypassed by the s -process when the ^{151}Sm may capture a neutron before decaying into ^{151}Eu . Similarly, the ^{205}Pb production is suppressed when the ^{204}Tl branch is open. Therefore, their production is reduced when the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ rate is lowered, as it happens for all the other isotopes of the main component, and a further decrease of their abundances occurs in case of a more efficient second (convective) neutron burst. As a result, the final mass fractions of both isotopes are reduced by 15% at the 95% lower bound.

To conclude, the present work reports a much improved calculation of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction rate at $T \sim 90$ MK, for the first time based on direct data inside of the Gamow window. The reduced uncertainty will help our understanding of the s -process branching points that are sensitive to the neutron density. We find that the new low-energy cross-section measurements imply sizeable variations of the ^{60}Fe , ^{152}Gd and ^{205}Pb yields. Other isotopes, whose production or destruction are influenced by close-by branching points, such as the two neutron-magic nuclei ^{86}Kr and ^{87}Rb as well as ^{96}Zr , are less affected by a variation of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction rate, mainly because of their higher initial (solar) abundance. However, we cannot exclude that larger changes may occur in models with different initial mass and composition. For this reason, a more extended set of AGB models is required to accurately evaluate the general impact on the galactic chemical evolution.

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